# Chapter 3

**Neutron Diffraction Studies on**

\( \text{La}_{0.325}\text{Tb}_{0.125}\text{Ca}_{0.30}\text{Sr}_{0.25}\text{MnO}_3 \) (LTCSMO) **Manganite**

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3.1 Introduction

A formidable amount of work has been devoted aiming towards the understanding of the structure and properties of colossal magnetoresistance (CMR) manganites [1]. Manganites are sensitive to changes in external conditions as well as composition and exhibit rather complex phase diagrams. Mixed valent manganites with the general formula $R_{1-x}A_xMnO_3$ ($R$ = trivalent rare earth ion and $A$ = divalent ion like Sr$^{+2}$, Ba$^{+2}$, Pb$^{+2}$, Ca$^{+2}$ etc.) are found to exhibit variety of phenomena such as charge, spin and orbit ordering, electronic magnetic and structural transitions depending on the type and/or amount of doping ($x$). It has been accepted that, the double exchange (DE) mechanism can not by itself account for all the observed effects, in the CMR materials [2, 3]. Other mechanisms involving, electron - phonon coupling [4], electron - magnon interactions [5], phase and charge segregation [6, 7] and other electronic effects [8, 9] have been proposed to explain the variety of observed phenomena. In the mixed valent manganites, Mn ion in Mn$^{+3}$ and Mn$^{+4}$ oxidation states, occupying the specific lattice sites, known as charge ordering is responsible for electron localization thereby restricting the hoping of electrons from one site to another. The doped manganites with doping level $x = 0.5$ such as La$_{0.5}$Ca$_{0.5}$MnO$_3$, La$_{0.5}$Sr$_{0.5}$MnO$_3$ etc have attracted the attention due to the interesting charge and orbital ordering correlation exhibited by them [10, 11]. These half doped manganites show transformation from a ferromagnetic metallic (FMM) to charge ordered (CO) antiferromagnetic (AFM) state at a certain temperature below Curie point ($T_C$) [10, 11]. The co-existence of AFM and CO states has its origin in long-range co-operative Jahn-Teller effect and regular alternate arrangement of Mn$^{3+}$ and Mn$^{4+}$ ions i.e. real space ordering of Mn$^{3+}$ and Mn$^{4+}$ ions [10]. It is reported that, charge ordered (CO) state in manganites is sensitive to chemical substitution at Mn site, A - site ionic radii mismatch, average size of A - site cations etc [12]. The A - site ionic radii mismatch leads to size variance $\sigma^2$ which is quantified as $\sigma^2 = \Sigma x_i r_i^2 - <r_i>^2$, where $x_i$ is a fractional occupancy and $r_i$ is the corresponding ionic radius. It is established that, size mismatch and disorder at A - site affect the MnO$_6$ octahedra and also Mn-O-Mn bond angles, play an important role in the modification of magnetic and transport properties of the manganites [13].
Consider the cases of half doped La$_{0.5}$Ca$_{0.5}$MnO$_3$ (LCMO), having $\langle r_A \rangle \sim 1.198\AA$ and insulator – metal transition temperature, $T_{IM} \sim 220$K and antiferromagnetic transition temperature ($T_N$) $\sim 170$K with $\sigma^2 \sim 3.24 \times 10^{-4}$ Å$^2$ [14] and La$_{0.5}$Sr$_{0.5}$MnO$_3$ (LSMO), having $\langle r_A \rangle \sim 1.263\AA$, ($T_{IM}$) $\sim 300$K and $\sigma^2 \sim 22.09 \times 10^{-4}$ Å$^2$ much higher than that of LCMO. The simultaneous substitution of smaller magnetic Tb$^{3+}$ ion and larger Sr$^{2+}$ ion at La$^{3+}$ site with the stoichiometric composition (La$_{0.325}$Tb$_{0.125}$)(Ca$_{0.3}$Sr$_{0.25}$)MnO$_3$ (LTCSMO) results into $\sigma^2 \sim 45.2 \times 10^{-4}$ Å$^2$ and $\langle r_A \rangle \sim 1.213\AA$ which is greater than that of LCMO and smaller than that of LSMO half doped manganites. This may result into the modifications in the structural, transport and magnetic properties of LTCSMO. It is reported that, with $x = 0.0 - 0.3$ in (La$_{1-x}$Tb$_x$)$_{2/3}$Ca$_{1/3}$MnO$_3$, $T_{IM}$ shifts toward lower temperature with resistivity suppression under applied field [15].

During the course of present work, the detailed temperature dependent neutron diffraction (ND) studies on La$_{0.325}$Tb$_{0.125}$Ca$_{0.3}$Sr$_{0.25}$MnO$_3$ (LTCSMO) compound were carried out to understand the effect of simultaneous Tb and Sr doping [Tb$_{(x)}$ = 0.125 & Sr$_{(2x)}$ = 0.25] in LCMO on the modifications in the structural behavior in the light of variations in Mn-O distances and Mn-O-Mn bond angles. The modifications in cell parameters, thermal parameters and various inter atomic distances as a function of temperature has been studied using neutron diffraction. In addition, the presence of coexisting magnetic phases, at lower temperatures, in the LTCSMO has been investigated using temperature dependent neutron diffraction studies.
3.2 Synthesis and Experimental Details

The bulk polycrystalline sample of \((La_{0.7-3x}Tb_x)(Ca_{0.3}Sr_{2x})MnO_3\) (LTCSMO) with \(x = 0.125\) was synthesized using conventional solid state reaction (SSR) method. Various steps involved in the synthesis of bulk LTCSMO samples are shown in fig. 3.1. The high purity starting materials, \(La_2O_3\), \(Tb_2O_3\), \(CaCO_3\), \(SrCO_3\) and \(MnO_2\) were mixed in stoichiometric ratio and calcined at \(950^\circ C\) for 24 hours. The calcined powder was then ground, palletized and sintered at various temperatures between \(1100 - 1375^\circ C\) with intermittent grindings.

![Diagram showing the synthesis process](image)

Figure 3.1 Schematic diagram of Solid State Reaction route used
The structural studies were carried out using Rigaku X-Ray diffractometer, to confirm the single phasic nature of the sample. The Neutron Diffraction measurements were performed at various temperatures (RT - 20K) using multiposition sensitive detector based powder neutron diffractometer on the beam line T-1013 at Dhruva reactor, BARC, Mumbai. The transport and magnetotransport properties were investigated using the D.C. four probe resistivity technique in the temperature range 45-300K with and without applied fields. The field cooled (FC) and zero field cooled (ZFC) magnetization measurements were carried out using VSM facility in the temperature range 5-325K to understand the magnetic behavior of the sample.

3.3 Structural Studies

3.3.1 X-ray Diffraction

Fig. 3.2 shows the XRD pattern (raw data) of LTCSMO with the reflections indexed using Powder-X software. The detailed structural information was obtained by fitting the XRD data using the Rietveld refinement technique employing Fullprof code [16]. Fig. 3.3 shows the Rietveld refined XRD pattern of LTCSMO compound. Refinement was done in different steps to achieve proper fitting parameters. Lorentzian 1 function was used to fit the XRD pattern. Very less difference between observed and calculated pattern reveals the reliability of fitted pattern. Within the instrumental resolution, no extra peaks were observed confirming the goodness of fit. LTCSMO crystallizes in orthorhombic structure having \( Pnma \) space group.
Neutron Diffraction Studies on La$_{0.325}$Tb$_{0.125}$Ca$_{0.30}$Sr$_{0.25}$MnO$_3$ (LTCSMO) Manganite

**Figure 3.2** XRD pattern of La$_{0.325}$Tb$_{0.125}$Ca$_{0.3}$Sr$_{0.25}$MnO$_3$

**Figure 3.3** Rietveld refined XRD pattern of La$_{0.325}$Tb$_{0.125}$Ca$_{0.3}$Sr$_{0.25}$MnO$_3$ (LTCSMO) Manganite
3.3.2 Neutron Diffraction

Neutron Diffraction (ND) is a powerful and popular technique, which is primarily used to determine the structure of crystalline materials. The temperature dependent Neutron Diffraction patterns were recorded on the multi-position sensitive detector based powder diffractometer on the beam line T - 1013, using wavelength $\lambda = 1.249\text{Å}$, at the Dhruva reactor, BARC, Mumbai in the $2\theta$ range of 6° to 140° at selected temperatures between 20 - 300K. For Neutron Diffraction experiment, powder sample weighing ~ 7 gms was filled in Vanadium container of 6mm diameter and attached to close cycle refrigeration (CCR) in order to investigate the temperature dependent modifications in the structural and magnetic behavior of the sample.

Fig. 3.4 shows the Neutron Diffraction patterns (raw data) taken at different temperatures. At 100K one can observe the emergence of peak at lower angle, $2\theta \approx 9^\circ$ which becomes more intense at 50 and 20K (as shown by arrow in the figure). At 20K two more peaks arise at $2\theta \approx 11.4^\circ$ and $13.3^\circ$, indicated by downward arrows in ND plot taken at 20K. Fig. 3.5 shows the magnified view of the low angle peaks observed in the ND patterns at 100, 50 and 20K in LTCSMO.
Figure 3.4 Neutron Diffraction patterns (raw data) recorded at different temperatures of LTCSMO
Pseudo-Voigt profile shape was used to fit the ND patterns collected at different temperatures because the Voigt function has one of the best symmetrical components for the peak shape which is used for constant wavelength X-Ray and Neutron Diffraction data analysis [17]. The Rietveld refinement using FULLPROF code was carried out in various steps. First, zero point of the detector with background parameters and scale factor were varied, followed by the variation in the full width half maximum parameters. Subsequently, general positions and thermal parameters were varied with the occupancies of the various atoms of the unit cell. In the last, magnetic phases were taken into account for ND patterns taken at 100, 50, and 20K and the moments of Mn$^{3+}$ and Mn$^{4+}$ ions were varied in both A-type and CE-type AFM phases. Figs. 3.6 (a-f) show typical Rietveld refined and fitted ND patterns of LTCSMO sample, data taken at different temperatures ranging between 20-300K. Detailed analyses of ND patterns yield interesting information about the nuclear and magnetic phases present in the sample. The values of various structural parameters, positions and refinement parameters at different
temperatures obtained from the Rietveld analysis are given in Table 3.1. These values indicate the goodness of fit for the patterns taken at different temperatures.

An attempt was made to fit the low temperature ND data of LTCSMO using the nuclear phase which resulted in the inability to fit some low angle magnetic peaks present in the data. Using A-type AFM phase, it was possible to fit the magnetic peak at $2\theta \sim 9^\circ$ in the low temperatures ND patterns taken at 100, 50 and 20K [shown by arrow in the figs 3.6 (d), (e) & (f)]. The other two low intensity peaks at $2\theta \sim 11.4^\circ$ and $13.3^\circ$ observed in 20K ND data [shown by asterisk* in the inset of fig 3.6 (f)] could not be fitted satisfactorily. In order to fit all the peaks present in the ND pattern at 20K, CE-type AFM phase was added, resulting in a complete profile fitting. This suggested the coexistence of two magnetic phases, namely, A-type and CE-type AFM phase present in the sample at 20K.
Neutron Diffraction Studies on La_{0.325}Tb_{0.125}Ca_{0.3}Sr_{0.25}MnO_3 (LTCSMO) Manganite
Neutron Diffraction Studies on La$_{0.325}$Tb$_{0.125}$Ca$_{0.3}$Sr$_{0.25}$MnO$_3$ (LTCSMO) Manganite

Graphs showing Bragg reflections for La$_{0.325}$Tb$_{0.125}$Ca$_{0.3}$Sr$_{0.25}$MnO$_3$ at 100K (d) and 50K (e) with observed, calculated, and difference intensities plotted against 2θ (degrees).
Figure 3.6 Rietveld refined pattern shows observed (o symbol) and calculated (line) Neutron Diffraction data for La_{0.325}Tb_{0.125}Ca_{0.3}Sr_{0.25}MnO_{3}, recorded at (a) 300K, (b) 200K, (c) 150K, (d) 100K, (e) 50K and (f) 20K. Tick mark below the diffraction profile mark the position of allowed Bragg reflections. The difference between the observed and calculated values is given at the bottom. [Inset of figure 3.9 (f) shows the A - type AFM phase indexed as (020) and CE - type AFM phase indexed as (01\frac{1}{2}) and (\frac{1}{2}1\frac{1}{2})]

The inset of fig. 3.6 (f) shows the low intensity magnetic peaks, indicating the characteristic of A - type and CE - type AFM phases respectively present in the sample at 20K. It is reported that, in charge ordered La_{0.5}Ca_{0.5-x}Sr_{x}MnO_{3} (LCSMO); x = 0.0 - 0.3, CE-type AFM phase exist below Sr_{(x)} = 0.4, above which, A - type AFM phase occurs in La_{0.5}Ca_{0.1}Sr_{0.4}MnO_{3} sample [18]. This indicates that, Sr - doping helps in the development of A - type AFM phase in the sample.
Table 3.1 Structural parameters of \((\text{La}_{0.325}\text{Tb}_{0.125})(\text{Ca}_{0.3}\text{Sr}_{0.25})\text{MnO}_3\) obtained from the Rietveld refinement of the neutron diffraction patterns collected at different temperatures.

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<td>((\text{La}, \text{Tb}, \text{Ca}, \text{Sr}))</td>
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<td>(R_{exp})</td>
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3.4 Transport Properties

During the course of present studies, the transport properties of simultaneously Tb$^{+3}$ and Sr$^{+2}$ doped (La$_{0.7-3x}$Tb$_x$)(Ca$_{0.3}$Sr$_{2x}$)MnO$_3$; $x = 0.125$ sample have been investigated and an effort is made to establish a structure-property correlation in this sample using the temperature dependent ND studies and transport and magneto transport measurements.

Earlier studies, by our group, on the resistivity behaviour of (La$_{0.7-3x}$Tb$_x$)(Ca$_{0.3}$Sr$_{2x}$)MnO$_3$; $x = 0.025 - 0.1$ samples by Rana et al [19] show that, the insulator-metal transition temperature ($T_{IM}$) decreases with increase in doping level ($x$) which has been attributed to the increase in the size variance. The presently studied (La$_{0.325}$Tb$_{0.125}$)(Ca$_{0.3}$Sr$_{0.25}$)MnO$_3$ (LTCSMO) sample, having $x = 0.125$ is different from the reported (La$_{1-x}$Tb$_x$)$_{0.7}$Ca$_{0.3}$MnO$_3$ system [15] in a way that, substitution of Sr$^{2+}$ along with Tb$^{3+}$ results in an increase in carrier density while in the reported system [15], it remains constant.

Figure 3.7 $\rho$ vs T plots of La$_{0.325}$Tb$_{0.125}$Ca$_{0.3}$Sr$_{0.25}$MnO$_3$ under various applied fields
It can be seen from fig. 3.7 that, under 0 and 1T fields, the sample exhibits insulating behavior with large resistivity value ($\sim 10.542\Omega \text{cm}$) due to the size variance effect. The robust orbital ordering at and below 100K leading to insulating behavior can not be broken under 1T field. However, under application of 5T field, the sample exhibits a broad insulator - metal transition at $T_{IM} \sim 73K$ which increases to $\sim 83K$ under 8T field. It can be observed that resistivity decreases with increasing applied field and $T_{IM}$ shift towards higher temperature.

To study and understand the electronic transport in semiconducting region doped manganites, mainly four models are reported in the literature.

1. Nearest neighbor hopping or the activation beyond the mobility edge given by
   \[ \rho = \rho_o \exp \left(\frac{E_a}{kT}\right) \] [20]

2. Adiabatic nearest neighbor small polaron hopping (SPH) model
   \[ \rho = AT \exp \left(\frac{E_a}{kT}\right) \] [21, 22]

3. Schklovskii-Efros (SE) type of Variable Range Hopping with a soft gap due to modification of density of states by Coulomb interaction given by
   \[ \rho = \rho_o \exp \left(\frac{T_0}{T}\right)^{1/2} \] [23]

4. Variable Range Hopping (VRH) of Mott type for uncorrelated carriers
   \[ \rho = \rho_o \exp \left(\frac{T_0}{T}\right)^{1/4} \] [24, 25]

To understand the nature of electronic conduction in the semiconducting region of the presently studied LTCSMO sample, an effort was made to fit resistivity data under different fields, using the above mentioned models. It was observed that the data fits best in the VRH model of Mott type for uncorrelated carriers, where $\rho_o$ is the residual resistivity and $T_0$ is related to carrier localization length. In order to understand the nature of electron conduction in LTCSMO, the $\rho - T$ data has been fitted in Variable Range Hoping (VRH) model, as shown in the fig. 3.8.
The values of activation energy, $E$, calculated using the equation $T_0 = \frac{E}{K}$ [K is Boltzmann constant ($8.617 \times 10^{-5}$ eV/K)] are 48.26, 47.72, 35.23 and 10.22 K at 0, 1, 5 and 8T fields respectively. It can be seen that, the activation energy decreases with increasing applied magnetic field suggesting that, the localization length is suppressed favoring the hopping of charge carriers from one site to another with increasing field.
3.5 Magnetotransport Properties

Due to the magnetoresistive properties of the manganites, they are very useful compounds from fundamental understanding as well as application point of view. Magnetoresistance (MR) is calculated using the formula:

\[
MR \% = \frac{\rho_0 - \rho_H}{\rho_0} \times 100
\]

where \( \rho_0 \) and \( \rho_H \) are the resistivities measured under the applied field of zero and \( H \), respectively. The resistivity measurement on the LTCSMO shows that it remains insulating up to 45K (under 0 and 1T fields) within the limit of resistivity instrument. The variation in MR calculated at 5 and 8T fields (under which metal-insulator transition was observed) is shown in fig. 3.9. It is clear that, MR increases with decreasing temperature and increasing field which can be attributed to the insulating nature of the sample under zero applied fields.

![Variation in MR with temperature under 5 and 8T fields for LTCSMO](image)

Figure 3.9 Variation in MR with temperature under 5 and 8T fields for LTCSMO
Considering this constrain during the course of the magneto transport studies on LTCSMO sample, the MR vs H isotherms in the field range 0 - 8T, were collected at 50, 100, 200 and 300K in order to understand variation in MR with applied field below T_P, around T_P and well above T_P. Fig. 3.10 shows the MR vs H isotherms obtained at various temperatures for LTCSMO sample.

![Figure 3.10 MR vs H isotherms collected at various temperatures for \( \text{La}_{0.325}\text{Tb}_{0.125}\text{Ca}_{0.3}\text{Sr}_{0.25}\text{MnO}_3 \)](image)

It can be clearly seen that, MR increases with applied field which can be attributed to the magnetic field induced suppression in magnetic disorder and reduction in scattering of the charge carriers. It is also clear that, high field magnetoresistance (HFMR), under 9T field, is suppressed with increase in temperature. The HFMR is ~ 50, 35, 19 and 5% observed at 50, 100, 200 and 300K. This can be understood in terms of increase in electron phonon coupling and lattice vibrations with temperature resulting in the reduction of HFMR. There is no any significant MR under low applied field indicating the absence of the role of microstructure.
3.6 Magnetic Measurements

In order to investigate the role of non magnetic Sr$^{+2}$ substitution along with magnetic Tb$^{+3}$ ion on the modification in magnetic behaviour of (La$_{0.7-3x}$Tb$_x$)(Ca$_{0.3}$Sr$_{2x}$)MnO$_3$ ($x = 0.125$) nearly half doped manganite, we have carried out magnetization measurements in the temperature range of 20 - 325K and under 150Oe field, both in Zero-field-cooled (ZFC) and field-cooled (FC) states using Vibrating Sample Magnetometer (VSM) at SSPD, BARC, Mumbai. Fig. 3.11 shows the $M_{FC}$ and $M_{ZFC}$ plots for LTCSMO sample.

![Magnetic Measurements Plot](image)

**Figure 3.11** ZFC and FC magnetization plots of La$_{0.325}$Tb$_{0.125}$Ca$_{0.3}$Sr$_{0.25}$MnO$_3$

Inset: Enlarged view of magnetization as a function of temperature

It is clear from the fig. 3.11 that, sample exhibits the Curie temperature $T_C \sim 47K$ ($T_C$ taken as the bifurcation temperature of $M_{ZFC}(T)$ and $M_{FC}(T)$ curves). Our earlier, group study, showed that, in the (La$_{0.7-3x}$Tb$_x$)(Ca$_{0.3}$Sr$_{2x}$)MnO$_3$ ($x = 0.25, 0.50, 0.75, 0.1 & 0.125$) series, $T_C$ continuously decreases with increase in doping level $x$ which has been explained as due to the size disorder, resulting in a random displacement of oxygen ions.
from their normal crystallographic positions [19]. As shown in inset of fig. 3.11, magnetization curve shows, two low temperature transitions obtained from the ND measurements (discussed below) first at \( \sim 47K \) which indicates the CE-type antiferromagnetic ordering while second at \( \sim 147K \) indicating the presence of A-type AFM ordering.

3.7 Discussion and Conclusions

In manganites, variations in structural parameters like lattice constants, Mn-O-Mn bond angles and Mn-O bond lengths play a crucial role in governing the physical properties and their correlations. In order to understand the structural changes with temperature in LTCSMO derived from the Rietveld refinement of ND data, the variation in lattice parameters, cell volume, Mn-O bond distances and Mn-O-Mn bond angles with temperature is shown in fig. 3.12 (a)-(d). It is clearly seen that, with decrease in temperature below 100K, lattice parameters a and c increase while b decreases appreciably with the corresponding decrease in cell volume. Such a behavior is normally observed in sample exhibiting CE-type AFM phase associated with orbital ordering [14]. At and below 100K, the marginal variations in cell parameters indicate the signature of orbital ordering results into the CE-type AFM phase [26]. The variation in Mn-O bond length with temperature plotted in fig. 3.12 (c) depicts that, there is no large change in Mn-O\(_1\) bond length except a slight decrease to lower value at 200K. The average Mn-O bond length remains almost constant over the complete temperature range studied. The two oxygen positions in MnO\(_6\) octahedron are nomenclatured as apical - O\(_1\) and basal - O\(_2\) respectively. The nature of variation in Mn-O\(_{21}\) and Mn-O\(_{22}\) bond lengths as a function of decrease in temperature is opposite indicating the MnO\(_6\) octahedral distortion. At and below 100K, the difference between Mn-O\(_{21}\) and Mn-O\(_{22}\) bond lengths decreases, suggesting the suppression in octahedral distortion. This observation is supported by the reduction in difference between Mn-O\(_1\)-Mn and Mn-O\(_2\)-Mn bond angles at 100K and below, due to the suppression in MnO\(_6\) octahedral distortion, as depicted in fig. 3.12 (d).
Using to the observed Orbital Ordering (OO) present at low temperatures in LTCSMO compound, sample exhibits insulating behavior. This OO can not be broken under the application of 1T field. However, under the application of 5T field, the sample exhibits a broad insulator - metal transition at $T_{IM} \sim 73$K which increases to $\sim 83$K under 8T field.
Figure 3.13  Integrated intensity vs T plot for low angle A - type AFM peak observed at lower temperatures for \((\text{La}_{0.325}\text{Tb}_{0.125}\text{Ca}_{0.3}\text{Sr}_{0.25})\text{MnO}_3\).

[Inset: Integrated Intensity (I) vs T plot for low angle CE-type AFM peak observed at low temperatures for \((\text{La}_{0.325}\text{Tb}_{0.125})(\text{Ca}_{0.3}\text{Sr}_{0.25})\text{MnO}_3\)]

In our LTCSMO sample, A - type AFM reflection, indexed in a \(\times 2b \times c\) unit cell having Pnma space group is \((020)\) while CE - type AFM reflections are indexed as \((01\frac{1}{2})\) and \((\frac{1}{2}1\frac{1}{2})\). For CE-type structure, there are two different occupancy sites for Mn\(^{3+}\) and Mn\(^{4+}\). At 20K, magnetic moments obtained from the Rietveld refinement for CE-type AFM phase are 2.258 and 3.794 \(\mu_B/\text{Mn}\) for Mn\(^{4+}\) and Mn\(^{3+}\) ions respectively while the magnetic moment of Mn\(^{3+}\) ion obtained in a-b plane is 3.271 \(\mu_B/\text{Mn}\) in A -type AFM phase. Fig. 3.13 shows the variation in integrated intensity of the A type AFM reflection \((020)\) with temperature below 200K for LTCSMO sample. Linear fit to the data points intercept X-axis at \(\sim 143\)K suggests an absence of A - type AFM ordering above this temperature. There is no evidence of enhancement in the intensity of the low angle fundamental Bragg reflections particularly below the ferromagnetic transition.
temperature, 47K. From the reported M vs T behavior [19], it is observed that, for a given field and temperature, M decreases with increase in x. Absence of signature of long range order in ND pattern indicates that, the moment is too small to be detected in ND measurements. However, coexistence of nano clusters of FM and AFM cannot be ruled out. The inset of fig. 3.13 shows the variation in integrated intensity of the CE - type AFM reflection with the temperature for LTCSMO compound indicating that the ordering temperatures of the two antiferromagnetic phases are significantly different. It is of interest to note that, the nature of magnetic structure, orbital ordering, and charge ordering behavior in LTCSMO is similar to that observed in half doped compounds where the ratio of Mn$^{3+}$ and Mn$^{4+}$ is 1:1. Similar observation of ‘Pseudo-CE’ - type magnetic structure has been reported in the case of Pr$^{0.7}$Ca$^{0.3}$MnO$_3$ [27].

The $\rho$-T plots highlighting an absence of semiconductor to metal transition under zero and one tesla fields and field induced transitions occurring at $\sim$ 73 and 83K under 5 and 8T fields, suggest the removal of robust orbital ordering at and below 100K under higher applied magnetic fields (5 and 8T). Mott type VRH model nicely fitted to the semiconducting region in the $\rho$-T plots shows the field induced suppression in localization length which results into the enhancement in hoping of charge carriers. The insulating nature of the sample under zero applied field provides an enhancement in MR with decreasing temperature which exhibit two slope behaviors, one upto 120K in which MR increases gradually while second, below 120K, in which MR increases sharply with decreasing temperature under 5 and 8T fields. The sharp increase in MR below 120K can be attributed to the zero field insulating behavior and field induced metallic nature under 5 and 8T fields.
References


